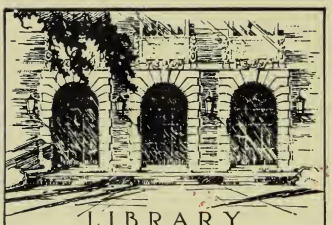

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TIME AND CHANGE

BY

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Fourteenth Annual Frederick William Reynolds Lecture

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The Reynolds Lectureship

The Annual Reynolds Lectureship at the University of Utah serves a double purpose.

First, through a distinguished member of its faculty, the University presents an important yearly offering to the public.

Second, the Lectureship commemorates in a fitting way the unique service of Professor F. W. Reynolds to the institution and to the State.

The committee on selection consists of ten members including the President of the University and the Director of the Extension Division. This committee acts upon recommendations of the Deans who are made responsible for nominating faculty members of outstanding accomplishment in their schools.

It is gratifying to the originators of this project and to those who have made contributions for its support that the Reynolds Lectureship has now become firmly established as a University function — promoted and administered by the University.

H. L. Marshall
President, Frederick William Reynolds Association

Lectureship Policies and a Point of View

From introductory remarks by the President of the Frederick William Reynolds Association at the first annual lecture, January, 1936:

"In these lectures, as the years go by, new knowledge, important subjects, and vital issues will be discussed. It is more than likely that some of these issues may be controversial in nature, about which differences of opinion and strong feeling may exist. But even upon such question it is proposed that the speaker shall be free to approach his subject with intellectual courage and vigor and advance any ideas which he can support with facts and logic.

"It is assumed, of course, that good taste shall not be violated, that propaganda in the narrower sense shall never intrude, and that due regard to the rights and feelings of others shall always be evident. But as long as the treatment of a subject is intelligent, objective, and critical, it is assumed that the speaker shall be free to follow facts and reasoning through to their conclusion.

"If such a policy, perchance, shall change some of our beliefs—then so be it. For beliefs are the framework upon which we do our thinking. Many present beliefs are the product of other times and other conditions—useful then, perhaps, but possibly hampering now. When certain beliefs hinder the effective use of intelligence, or hamper our adjustment to new conditions in a rapidly changing world, then more helpful beliefs become priceless—and desirable even at the expense of some temporary loss of tranquility.

"The products of intellectual activity and scientific investigation are to be brought here, not the reiteration of uncritical traditional views. On no other basic premise can a Frederick William Reynolds Lecture be true to its name—or be even worthy of its name."

TIME AND CHANGE

The World We Live In and the Laws of Chance

Like old-fashioned clocks, everything in the Universe is running down or at least such is the scientific dogma known as the second law of thermodynamics. The century old paradoxes raised by this law are still with us. If our expanding Universe were born two or three billion years ago as the radioactive clocks and the red shift in the spectra of nebula suggest, what then antedated the Universe's birth and how did it get wound up so that it could run down? One suggested answer is that the whole incident is a chance occurrence. The sample of the Universe which our largest telescopes show us is supposedly only a drop in the ocean of space, and 2½ billion years is only an instant in eternity. If we wait long enough and look far enough sometime, somewhere we find that matter and energy surge together in a catastrophic creative process and a new system of galaxies is born. This new system then methodically runs down over a period of billions of years, finally to reach an almost eternal state of rest. However, in some far away time and in a far corner of the Universe this fantastically improbable birth, maturation and decay starts all over again. Nothing the human mind can conceive of is more mathematically improbable than this birth of a Universe. Nevertheless, science, as yet, has nothing better to offer. The alternative is to discover some more orderly way of winding up the Universe which leaves much less to chance.

Nevertheless, it is a fascinating and scientifically profitable undertaking to see how far and how well the world about us can be explained as the operation of the laws of chance. In fact, it turns out that the theoretical chemist is essentially a gambler who builds up expectancy tables for the behavior and life time of molecules much as the actuaries of insurance companies prepare the tables for life expectancy of human beings.

The Fine Structure of Our World

Everything material is made out of atoms joined together through the sharing of electrons between pairs of atoms to make the so-called chemical bond. The number of bonds an atom is capable of making with neighbors is its valence. Depending on the atom, this may run from no bonds to eight. If an atom is capable of making at least two bonds, it can act as a link in a chain. Atoms making three bonds can combine to make a fabric and four valent atoms can combine with each other to fill up space. There are now 96 known elements with valences running from zero to eight and a great many of the conceivable ways of linking them together have been realized so that we know how to make in the neighborhood of a million different compounds.

By long experience chemists have discovered many possible methods of breaking one type of bonds without at the same time affecting the other types. This is usually done by adding appropriate types of molecules and cooking the mixture at the proper temperature for a

sufficient length of time. If the vulnerable bond is present, one gets new kinds of molecules which can be identified from their properties. With this method of finding what bonds break and which known molecules are formed when this particular set of bonds is broken, it is possible eventually to identify the structure of the most complicated molecules. In this way classical organic chemists have succeeded in determining the structures of exceedingly complicated molecules. The characteristic absorption of light by particular bonds is one of a number of the important newer physical methods which serve to identify bonds and so establish structure. X-ray measurements of interatomic distances is becoming of increasing importance. In establishing the structure of the wonder drugs, penicillin, streptomysin and chloromycetin, physical methods were almost as important as chemical procedures.

Chemical Change

The method by which molecules break one bond and form others is well understood. As Arrhenius pointed out long ago, molecules only occasionally collide with sufficient violence that certain atoms forget to which partners they were bonded and depart with new companions. A very specific thing about bonds is the energy required to break them. To understand the significance of this we require some preliminary considerations. The energy possessed by a molecule is proportional to the temperature. In fact, each of the molecules in the air of a room has on the average the same amount of energy associated with its east-west motion, its north-south motion or its up-and-down motion. Further, the amount of this energy is the same for all molecules, be they heavy or light. Each of these types of motion, as for example the east-west motion, is spoken of as a degree of translational freedom. Six hundred and two, thousand, million, million, million molecules is called one mole of molecules. Now a mole of air molecules weighs one-fourteenth of a pound and has an amount of energy associated with the molecular north-south translational degrees of freedom just equal to the temperature, provided we use the scale of temperature invented by Lord Kelvin. At room temperature this is 300 calories and is one ten-thousandth of the 3,000,000 calories a moderately hard worker needs for a day's nourishment. The kilocalory or Calory is 1000 times the small calory, so that the daily required nourishment of a worker is ordinarily spoken of as 3000 Calories.

A Typical Experiment

Let us now consider a very famous reaction. If a glass jar containing water with a little table salt dissolved in it has two copper strips dipping into the water and these two strips are connected together by wires which carry the current from three or four new dry cells, one will observe oxygen gas coming off of one copper strip and twice as much hydrogen gas coming off from the other strip. If a quart of water is decomposed in this way one gets about 1400 quarts of hydrogen gas and 700 quarts of oxygen. One can store the two gases separately in closed containers forever and nothing will happen. On the other hand,

if you mix them and store the mixture, the grim reaper is waiting just outside your door. The quart of decomposed water has considerably more potency as an explosive than a quart of dynamite. Nevertheless, if you are lucky, you might keep the mixture around a lifetime without its going off. A spark or flame in the mixture, however, will insure a final settlement within a few millionths of a second. A less obvious but equally effective way of setting off the mixture would be to add a pinch of powdered platinum catalyst, since it enormously hastens an otherwise very slow reaction. We shall have more to say later about catalysts and how they operate. Living things could not persist for an instant without an almost endless number of catalysts ordinarily referred to as enzymes.

Time and Distance in the Atomic World

The world of everyday affairs is described nicely in terms of length in centimeters and time in seconds. A centimeter is 2/5ths of an inch. Events among the atoms are much more conveniently described in terms of what we shall call micro units. Thus lengths are measured in hundred millionths of a centimeter or angstroms. Time is measured in thousand, million, millionths of a second or jiffies. At room temperature, the average hydrogen atom is moving a hundred thousand centimeters per second. In micro units, this is one angstrom per jiffy. Since the molecules carry sound, their velocity is the velocity of sound. This velocity is almost exactly one hundred times as fast as the speediest human can run. In micro units, we take the mass of the hydrogen atom as the unit of mass and the charge of an electron as the unit of charge. Thus the energy, E, of a hydrogen atom, of a mass m $= 1$, moving at a velocity, v, of one angstrom per jiffy is

$$E = \tfrac{1}{2}\ mv^2 = \tfrac{1}{2}\ 1 \times 1^2 = \tfrac{1}{2} \text{ junior erg or } \tfrac{1}{2} \text{ jerg.}$$

A simple calculation shows that the ordinary erg is equal to sixty million million jergs. The average energy in any fully excited bond at room temperature is 6/5 of a jerg. Such a bond has one jerg of vibrational energy at 250° on Kelvin's scale of temperature. The junior volt or jolt is a larger unit of energy which is useful when we want to talk about the work required to break a bond or pull an electron out of a molecule. One jolt is the energy required in vacuum to separate to infinity one unit of positive charge from one unit of negative charge when the charges are one angstrom apart. Thus, to ionize a hydrogen atom requires .934 jolts or 623 jergs. To break the bond between two hydrogen atoms requires 206 jergs or .305 jolts. Planck's constant in micro units has the value of 4 jerg jiffies, while the lifetime of a molecule in the activated state in micro units is 1.8 jiffies. Finally all types of molecules make on the order of a vibration per jiffy. This illustrates the general scientific result that a system of units can usually be found for related phenomena such that the value for all observed results approximates unity. An interesting alternative to the above micro system would be to use the diameter of the Bohr orbit for hydrogen (1.08 angstroms) as the unit of length and make some other changes which we need not elaborate here.

Rates of Chemical Reactions

Let us consider how the hydrogen molecule, H_2, containing two hydrogen atoms reacts with the oxygen molecules, O_2, containing two oxygen atoms to make water, H_2O, containing one oxygen and two hydrogen atoms. Now, if two molecules of hydrogen could bump into a molecule of oxygen and make two molecules of water, there would be nothing left over. This process is indicated symbolically by writing the reaction

$$2\,H_2 + O_2 \rightarrow 2\,H_2O.$$

The molecules pay no attention to this neat way of reacting, but instead go through a series of successive steps.

$$H_2 \rightarrow 2\,H - 102.8$$
$$H + O_2 \rightarrow OH + H - 14$$
$$O + H_2 \rightarrow OH + H + 1$$
$$OH + H_2 = H_2O + H + 12$$

The first equation indicates that a hydrogen molecule breaks into two hydrogen atoms provided 102.8 Calories are furnished to a mole of hydrogen molecules. In the last two equations the plus signs mean the reaction gives off heat to the amount indicated by the 1 and 12 Calories respectively. Reactions of this type which give off heat go rapidly. Where much heat must be supplied, the reactions go only when the necessary energy accidentally becomes accumulated so that the big energy splurge becomes possible. If we expressed the energy involved in these reactions in jergs, they would be just twice the corresponding values in Calories.

The guiding principle with molecules is to economize energy, just as with people, processes occur oftener if they are economical of money. Building on the statistical mechanical laws laid down and elaborated by Willard Gibbs, Arrhenius and many others, the speaker in 1935 was finally able to formulate the general law for the rate of all structural rearrangements both inside and between molecules. This general law of reaction has the rather forbidding form

$$k' = \varkappa \frac{kT}{h} e^{-\frac{\Delta F^{\ddagger}}{kT}}$$

Here k′ is the rate at which the reaction takes place when the substances which react are at unit concentration. This rate of reaction, for example, doubles as we double the concentration of each molecule that enters into the complex of molecules which must simultaneously collide in order that the reaction takes place. This complex is spoken of as an activated complex. The factor $e^{\frac{-\Delta F^{\ddagger}}{kT}}$ is just the ratio of activated complexes to reactants. $\frac{kT}{h}$ is the rate of decomposition of activated complexes and $\varkappa$ which is generally unity, is the chance that, if a particuar complex decomposes, it will not immediately reverse itself. For the sophisticated, we may further say that k, T, h, e, and $\Delta F^{\ddagger}$ are the Boltzmann constant, temperature Kelvin, Planck's constant,

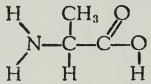
base of natural logarithms and the work which must be done in forming the activated complex from the reactants, respectively. For a typical reaction which is half over in a half-hour at room temperature, the quantities have the following values in micro units. The frequency $\frac{kT}{h}$ has the value .56 in reciprocal jiffies; $kT = 6/5$ jergs and $\Delta F^{\ddagger} =$ 50 jergs. $\frac{\Delta F^{\ddagger}}{kT} = 42.5$ and being dimensionless, of course, is independent of the units. Thus if $\Delta F^{\ddagger}$ is twice as large, it will be necessary to double kT to have the same rate of reaction. Clearly the free energy of activation is the determining factor in the specific rate of reaction. The rules for estimating the energy of activation are fairly well known. Thus the energy of activation is greater, the stronger the bonds which are to be broken. In the reaction $H_2 + I_2 \rightarrow 2HI$, the H_2 bond has a strength of 102.8 Calories per mole, the I_2 molecule, 39 Calories, while the activation energy is 28% of the sum of these two bonds or 40 Calories. In general, when a reaction breaks two bonds and replaces them with two new ones, the energy of activation is 28% of the sum of the strengths of the two bonds broken, providing the reaction is proceeding in such a way as to make bonds which are stronger than those broken. This type of reaction is called a bimolecular reaction between saturated molecules. The activation energy in the reverse direction is greater than this by the difference between the strengths of the final and initial bonds. If a reaction breaks a bond without replacing it with anything, the activation energy is equal to the strength of the bond broken. Such a reaction is called a unimolecular reaction. When a molecular fragment having an unsatisfied valence, such as a hydrogen atom, reacts with a saturated molecule, i.e., a molecule with all of its valences satisfied such as O_2, the activation energy is roughly 5% of the bond broken providing the bond made is stronger than the bond broken. The activation energy for the reverse reaction is greater by the difference between the bond of the product and of the reacting molecule.

It should now be clear that, if one knows the strength of the bonds that are to be broken, one can estimate the temperature to which a system must be heated to get reactions to occur in a given time. Conversely, the rate of reaction at a particular temperature indicates the type of bond which is being broken. This correspondence between bond strength and rate of reaction is the secret of the organic chemists' tremendous success in deducing molecular structure from rates of reaction. All the physical changes in the world which don't involve the motion of matter in bulk are to be explained in terms of the general principles outlined above. It is interesting to consider some special examples involving living things.

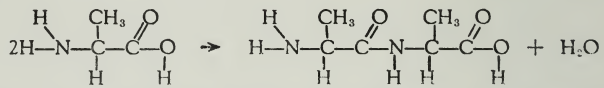
The Chemistry of Luminescence

Almost everyone has seen the flashing of the firefly or of the glowworm and wondered how they do it without getting hot. Newton Harvey has written a fascinating book on the subject which he calls 'Living Light." Actually this ability of making light is possessed by a wide variety of living things, including various types of bacteria as well

as the small crustacean Cypridina which inhabits the ocean off the coast of Japan. About forty specimens of Cypridina laid side by side just cover the thumbnail. The light organs can be stripped from these organisms and put into two glass jars. One jar can then be extracted with hot water and the other with cold. Neither extract now glows by itself but, if the two extracts are mixed, one gets a bright light. The cold water extract contains a protein enzyme, luciferase, and the hot water contains luciferin, a somewhat remote relative of the sugar molecule. Light is liberated when an energetic oxygen molecule violently collides with the luciferin and steals its electrons. At high enough temperatures, this act of oxygen plundering luciferin could occur without the help of the protein enzyme, luciferase. But with luciferase wrapping itself around both the oxygen and the luciferin, much less violent collisions are necessary and the reaction takes place at ordinary temperatures. The luciferase is formed from about 200 amino acids joined end-to-end to form a long, snake-like chain. This snake, in addition to the amino acids, has two or three special so-called prosthetic groups built into it which attach directly to the reacting oxygen and luciferin molecules. A typical amino acid has the formula



and two of these amino acids join together by splitting out water as follows:



This process of attachment continues until about two hundred amino acids are joined together with two or three of the reactive prosthetic groups included. In water, the normal position for this long snake-like molecule is for it to be coiled up. This is because the oily groups of the amino acids such as CH_3 abhor water and, by folding up the molecule, can place such groups next to each other. Also, NH_2 groups like to be next to C = O groups. This power of attraction is intensified when the groups carry charges, as is the case with NH_3^+ and $C(=O)-O^-$. Two such charged groups juxtapose to form what is called a salt bond.

When oxygen steals electrons from luciferin most of the luciferin molecules do not give off light or luminesce. This is because the oxygen almost always is polite and takes the top electrons, but about once in every hundredth time the oxygen gets in a hurry and dips deeper for its electrons leaving an outer electron attached to the luciferin. This outer electron is whirling above the abyss left by its departed companions and, after about one one-hundred-millionth of a second, it drops into the chasm with a jar which detaches a green bullet of light or quantum of light, which shoots out into space and strikes the eye. Thus we can tell exactly how fast this oxidation of luciferin is proceeding by the brightness of the light, since brightness is proportional to the number of bullets shot out.

Luminescent bacteria are ideal for studying what happens to luciferase, a typical member of the all important enzyme family. At ice temperature the bacteria give practically no light. As the temperature is raised, the bacteria glow brighter exactly as happens in any normal chemical reaction. This is because, with rising temperature, collisions become more violent and a larger fraction of the collisions are such that oxygen penetrates the luciferin and detaches the necessary electrons. At about half-way from freezing to blood temperature, a strange thing happens. Instead of the bacteria continuing to grow brighter with rise in temperature, the brightness starts falling off until, by the time blood temperature is reached, they have almost stopped glowing. If one quickly cools the solution containing the bacteria, they glow as brightly as before but, if they are kept at the high temperatures, there is a permanent loss of the power to glow.

The following picture leads to a quantitative explanation of this phenomena. At the half-way temperature, the enzyme molecules start to become heat prostrated and quit working at their job of being enzymes. This is a progressive process with a larger fraction of the molecules becoming prostrated as the temperature rises until, when blood temperature is reached, substantially all of the enzyme molecules have collapsed. If they are held at this high temperature, the enzyme molecules shake themselves to pieces or in effect die. However, if they are quickly cooled they go back to work without suffering permanent damage.

The process of heat prostration is a substantially complete unfolding of the enzyme molecule which carries it into a state where it can no longer wrap itself around the oxygen and the luciferin and hasten their reaction.

The unfolding process brings many oily groups into contact with water. The water recoils slightly, making the whole system expand and occupy more space. For enzymic heat prostration, this expansion is about 75 c.c. per mole of enzyme molecules. The famous Braun-LeChatelier principle says that any change which can occur with a decrease in volume will be favored by high pressure. Thus, one predicts that at high temperatures pressure will increase the light intensity by forcing the heat prostrated molecules back into the active smaller folded-up volume. The prediction is, of course, fulfilled. The fact that 500 atmospheres pressure makes the bacteria near blood temperature almost twice as bright enables us to calculate that the expansion is 75 c.c. per mole. In the low temperature range where all the enzyme molecules are active, increasing the pressure by 500 atmospheres decreases the light intensity by a factor of nearly 3. This proves that in order for reaction to take place the coiled-up, snake-like enzymes must partly unfold, thus increasing the volume by 50 c.c.'s per mole. This, of course, is intermediate in volume between the coiled-up state and the completely uncoiled, inactive state which is 25 c.c. more expanded. The uncoiled state is enormously more disordered than the coiled-up state. Technically, this is shown by an increase in entropy of 300 E. U. and an increase in energy of 60 Calories. Such large heat and entropy changes insure that the enzymes change over a very short temperature range from the coiled to the uncoiled state.

If, to a jar of brightly glowing bacteria about ten degrees above freezing, we add one per cent of alcohol, the light goes out. If less alcohol is added, it is dimmed less and, if one analyzes the dependence of brightness on alcoholic content, one finds that three molecules of alcohol must combine with each enzyme molecule to incapacitate it. Further, if one puts drunken enzyme molecules under pressure, they give up the alcohol and go back to work. This proves the alcohol adds to the interior bonds of the enzyme, causing it to unfold in the same way that heat does, and pressure similarly neutralizes the effects of both heat and alcohol. All kinds of alcohols, ethers, acetone and many other similar substances have this same effect of stopping bacterial glow by virtue of three or four molecules combining with and inactivating the enzymes.

The effect of ether and alcohol on the central nervous system is similar. Among the enzymes inactivated in the central nervous system will be those which aid oxygen in burning sugar and similar molecules in the cells of the central nervous system. If this burning slows down, the nerve cells cease to carry the signals which lie at the basis of consciousness. Here, as with luminescence, the enzymes recover if the inactivation isn't too complete or kept in effect too long.

If a few hundredths of a per cent of sulfanilamide is added to the solution containing luminescent bacteria, the light goes out as in the case of alcohol. Only one sulfanilamide molecule is required to inactivate one luciferase, instead of the three. Pressure does not undo the sulfanilamide inactivation as it does that due to alcohol. The sulfanilamide inhibition of luminescence is entirely analogous to the effect of sulfa drugs in preventing bacterial growth. The prevention of bacterial growth is due to sulfanilamide wasting a position on the enzyme by occupying that position which would otherwise be used by a hard-working para amino benzoic molecule. The effect is apparently similar with luminescence except that para amino benzoic acid, even though it occupies the enzyme position, does not help luminescence.

The observed behavior of luciferase is apparently typical of the vast majority, if not of all, the enzymes which make life possible. The list of enzymes for which temperature, pressure, and inhibitors have been studied is constantly growing. The papers of Professor Frank Johnson in collaboration with the speaker and later papers of Johnson and others should be consulted for much additional material.

Optical Activity and Catalysis

If a molecule and its image in a mirror are compared, they may be indistinguishable or they may be related to each other as a left and a right hand. If one passes light successively through two sheets of polaroid cut from the same piece, one finds that a maximum of half the light gets through when the two sheets both have their north end up. If now one sheet is rotated through 90° so that either its east or west end is up, no light gets through. Light is a wave motion much like a rope tied at one end and caused to vibrate by moving the other end. If the rope goes through two picket fences, it can vibrate when the pickets in the fences are parallel but not when they are at right angles. The polaroid sheets act exactly like the picket fences.

If one dissolves a lot of left-handed molecules of sugar in water and puts them in a tube between two sheets of polaroid, the maximum amount of light gets through when the sheets are rotated with respect to each other. The more sugar dissolved, the more the rotation that is required to give maximum brightness. In fact, this is the standard way of analyzing sugar used in the local sugar factories. The scheme works because nature specializes on left-handed molecules. When a chemist synthesizes molecules by the usual methods, he gets equal amounts of both left- and right-handed molecules. This is the most compelling proof that nature always hammers out its molecules on catalysts which act as patterns to which the constituents of the growing molecule adhere until the molecule is finished. The finished molecule then disengages itself and starts its separate existence—often as an enzyme itself. Nature's all but universal preference for left-handed molecules could be understood if all living things originated from a single pattern. This is a possible but not a necessary explanation. Any enzyme which is to act as a pattern must first unfold. This necessarily means that it greatly increases its entropy and volume in passing into the activated state. This enables us to predict temperature and pressure effects which are in accord with known experimental results.

Some Chemical Effects in Nerves

A c.c. of blood contains some five billion red blood cells. Since a man has a volume of the order of 70,000 c.c., he clearly has more cells in him than there are dollars in the national debt. Each of these cells is much like a highly specialized bacterium with a membrane around it about 50 to 100 angstroms thick. Inside the cell are chromosomes and genes and the other enzymes which make us what we are. This is obviously true since each of us has developed from the union of a single sperm with a single ovum and all our physical potentialities were crowded into the chemical properties of the molecules making up this pair of cells. Each of these cells must get its nourishment through the cell walls in the form of substances related to the sugars, proteins, and fats. The sugars, in particular, are uncharged molecules but when they burn inside the cell with oxygen, they break up into an equal number of positively and negatively charged particles. Because the positively charged particles escape more readily through the membrane, there is left an excess of negative charge inside the cell with an excess of positive outside. This results in a nerve cell in its resting state having a potential across its membrane of about .05 of a volt. This potential acts to keep the molecules in the membrane fitted tightly together and relatively impervious. If anything is done to make this potential drop by as much as .01 volt in a spot on the cell, this part of the cell immediately becomes leaky. The charge from neighboring regions then leaks out of this spot. The voltage of the neighboring region drops and so the disease spreads throughout the whole nerve. At the point where this nerve comes close to others the changed voltage and material liberated into the interspace because of the nerve's leaky condition may start a leaky spot in a neighbor and so the impulse may travel on to a spot in the brain. A complex of such signals

coming from various nerve endings gives our varied sense impressions. In the process of getting leaky, certain enzymes are exposed—apparently in the membrane itself. This speed-up in the burning of sugar greatly speeds up the formation of positive and negative charges and, by differential leakage, builds up a high enough voltage, even with the leaky membrane, so that the membrane changes back into its impermeable form. It now is ready to be stimulated again. If the stimulus is intense, each nerve repeats often and many nerves fire. It is a fascinating aspect of enzyme chemistry to attempt to make sense out of the tremendous literature in this very important field and to connect it up with such things as luminescence. The medical school at the University of Utah is outstanding in this field and is continually publishing interesting results.

Photosynthesis

We can not here more than touch the research in this vital field of catalysis. Briefly, four photons strike a chlorophyl molecule and knock electrons, ε, into higher states where they are easily detached by a carbon dioxide molecule, CO_2, which at the same time appropriates four hydrogen ions, $\overset{+}{H}$, from the water according to the following reaction:

$$4\,\varepsilon + 4\,\overset{+}{H} + CO_2 \rightarrow HC{-}O{-}H + H_2O$$

Six of the H—C—OH finally join in a ring to make sugar, which is the basic product of photosynthesis. Since the sugar synthesized is all of the left-handed variety, we know our enzymes are getting in their subtle blows here also. Now the poor bereft chlorophyl looks around for a source of four electrons to restore it to its original state and steals them from two water molecules. In the process it liberates an O_2 molecule and four hydrogen ions back to the solution. Doctors Spikes and Lumry with Mr. Wayrynen have found that they can measure the rate at which these photosynthetic products appear by simply sticking a piece of metal into the green extract from spinach leaves and reading the change of voltage as light shines on the extract. For a constant light intensity the voltage change shows the amount of material synthesized is proportional to the time of illumination. Very reproducible results are obtained if sufficient care is taken in the preparation of the extract and in the control of the conditions of the experiment. Extracts from different plants give interesting variations in the results, but all of them show the expected peculiarities of plant enzymes.

It has only been possible to sketch very briefly a few of the fascinating laws and the changes with time which confront us whenever we concern ourselves with the molecular fine structure of this world in which we live. It is here we must work if we would shape our physical environment nearer to the heart's desire.

Finally, I want to thank my associates for valuable discussions—especially Dr. Rufus Lumry and Mr. Walter Woodbury. It is likewise a pleasure to express my appreciation to the Reynolds Lecture Committee for setting me this interesting task.

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Marshall, H. L.
Martin, Almira M. D.
McPhee, Mary Shields
Moffatt, David W.
Moorhead, Mary
Morris, Thornton D.
Moyer, James A.
Moyle, Henry D.
Musser, Burton W.

Neff, S. B.
Nelson, Esther
Noall, I. S.

Ogilvie, Orin A.

Pack, Frederick J.
Pickering, Mrs. Harold W.
Reynolds, Mrs. F. W.
Ritter, Willis W.
Romney, G. O.
Rosenbaum, Mrs. Edward
Rosenblatt, Mollie
Rosenblatt, Morris
Rowe, Alice E.
Runzler, W. T.

Scott, Almere L.
Shields, Dan B.
Shields, Estella K. W.
Smith, Joseph F.
Smith, Mrs. Joseph F.
Smith, Mary B.
Stephens, Virginia Bush

Thody, Louis A.
Thomas, Elbert D.
Thomas, Mrs. Elbert D.
Thomas, George
Tugman, Orin

Van Cott, Mrs. Cleo G.
Van Cott, Lucy M.

Wahlquist, J. T.
Wallace, A. C.
Wallace, Elen
Wallace, Mrs. George H.
Wallace, Henry A.
Wallace, John M.
Wallace, William R.
Wallace, William R., Jr.
Ware, Florence
Ware, Walter E.
Ware, Mrs. Walter E.
Watson, Martha J.
Widtsoe, Rose H.
Winters, Elizabeth B.

Young, Levi Edgar